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Finite element modelling of the pyrolysis of wet wood subjected to fire

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ABSTRACT

The modelling of the pyrolysis of wet wood provides more realistic fire scenarios for structural fire design by taking into account variable thermal properties of wood which are beyond the scope of conventional structural fire design codes. The proposed numerical methodology has been written in MATLAB environment. A 2D nonlinear finite element analysis (FEA) is performed to model the pyrolysis of wet wood subjected to high temperature. The varying of thermal proprieties of wood are discussed from the point of view of changes of structure and chemical composition under fire condition. The validity of the model is established by comparing the predicted results with results from fire resistance tests presented in literature. Qualitatively, the model provides good agreement with the experimental data. It is shown that the model can handle layers of a wooden composite structure. Temperature profiles at different points in the wood sample and the two-dimensional charring depth of Laminated Veneer Lumber (LVL) panels are calculated and compared with experimental data.

1. Introduction

Timber structures have been designed in order to be able to maintain their strength and stability for a period time to ensure life safety and property protection under fire environment. Wood has been a leading structural material for a long time, and has been known to have excellent fire resistance due to its high thermal efficiency.

In recent years wood has been widely used in construction. But wooden structures must be considered with special care since timber is combustible material and constitutes a substantial fraction of the fuel load in fire condition. Analytical approaches and experimental testing are needed to assess the fire performance of a timber structure and several studies focus on the pyrolysis of cellulosic materials [1–11]. These studies have mainly focused on the influence of heat flux, moisture content, chemical composition of the sample, solid conversion and evolution rate of the volatiles. Shen et al. (2007) in [2] developed a one-dimensional pyrolysis model using finite-difference method in order to examine the influence of heat flux, species and moisture rate on the process of thermal decomposition of wet wood. The model was validated by comparing theoretical predictions of the temperature profiles at different points and solid conversion with experimental data. An effective alternative for simulating the pyrolysis behaviour of wet wood exposed to fire are numerical models based on the finite element method using two-dimensional elements, whose the predicted results are very realistic compared with one-dimensional model results because the charring process is usually different along the two directions composing the plan as shown in [12–14]. Therefore, the first purpose of this paper was to propose a nonlinear finite element analysis in order to complete the experimental and numerical studies of the pyrolysis of wet wood under external heat flux presented by Shen et al. (2007) in [2]. Knowledge of the thermal decomposition of wood is necessary and is of great interest owing to the importance of the pyrolysis process producing combustible gases, water vapour and char, and plays an important role in the phenomena of reaction to fire of materials, such as ignition and fire growth. The pyrolysis phenomenon of timber is defined as a complex interplay of chemistry, heat, and mass transfer. It changes timber to char and gases and then, modifies the density, the thermal conductivity and the specific heat of material [9,15–19]. The process of thermal degradation is observed when the temperature of timber reaches a certain threshold value (around 300 °C) which depends on the specie of wood [1]. The study of the pyrolysis process of wood as a porous media is rarely taken into consideration in the numerical analysis of charring in fire environment. The challenge to modelling the structural response of timber in fire is the accurate analysis and representation of these many processes. Knowledge of these processes and how they interact is important to understand the fire behaviour of timber structures.

For modelling of the pyrolysis of wet wood in fire only little information on charring, effects of moisture content, shrinkage of sample volume and gas momentum are available. Few numerical

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Nomenclature

T	Temperature [K]
t	Time [s]
x, y	Cartesian coordinates [mm]
c_p	specific heat [J/kg K]
λ	thermal conductivity [W/m K]
ρ	density [kg/m^3]
α	average absorptivity
Q_r''	energy source [kW/m^3]
q_e''	external heat flux per area [kW/m^2]
q_{loss}''	heat losses per area [kW/m^2]
Δh	standard reaction heat [kJ/kg]
k	reaction rate [1/s]
A	pre-exponential factor [1/s]
R	gas constant (R=8.314 J/mol K)
E	activation energy [kJ/mol]
X	moisture content of wood [%]
σ	Stefan–Boltzmann constant [W/m^2 K^4]
ε	emissivity
h_{conv}	convection coefficient [W/K m^2]
T_0	Initial temperature [°C]
T^*	Prescribed temperature [°C]
T_∞	ambient temperature [°C]
T_{iso}	ISO standard temperature [°C]
T_{ext}	furnace temperature [°C]
N_i	shape functions
[C]	unsteady temperature-change matrix
[K]	temperature stiffness matrix
{F}	temperature vector
u	horizontal depth [mm]
v	vertical depth [mm]

Subscript

w	wood 0 initial
c	char 1 char formation
l	liquid 2 volatiles formation
v	vapour 3 water evaporation
g	gas
s	solid

studies have been carried out and have added the effect of moisture rate [1–2], structural changes [9,20–21] and gas movement inside the solid [10,11]. Nevertheless, in order to better understand the influence of heat flux and moisture content on the pyrolysis process of wet wood, a complementary analysis is thus necessary, which is the second aim of this work.

Finite element modelling is an effective and inexpensive alternative approach to investigate the thermal behaviour of timber structures in fire environment without performing expensive fire testing. It is thus of interest to develop numerical models calibrated on available experimental results in literature to understand more details of the pyrolysis behaviour for wood members under fire conditions. In this work, the governing equations of the heat transfer in porous media, like wood, were provided by two different models (Luikov's model (1966) in [22] and Shen's model in [2]) by taking into account the variable thermal properties of wood. The paper presents the main results of a series of small-scale fire tests carried out by Shen et al. (2007) in [2] and Menis A. (2012) in [12] where the experimental tests were compared with predicted results obtained by using simplified design methods proposed by current codes of practice and recent research proposals. Numerical methods provide overall acceptable estimations of fire behaviour of wet wood members, especially considering the high variability that characterize the wood material and the experimental tests. Particular attention is given to the distributions of temperature and the formation of char in the cross-section of timber sample at different times after the exposure to fire.

2. Analytical models

This paper presents two models to describe the pyrolysis process of wet wood exposed to fire; the first assumed the all thermal properties of wood (thermal conductivity, specific heat and density of material) depend on temperature; the second considered the specific heat remains constant, only thermal conductivity and density of material which are temperature dependent. The objective of developing these tools, validated by experiments, is to help the engineering community and the standards organizations in taking fire into account as a potential structural load.

2.1. Classical model and governing equations

The reader may refer to [1,19] for a detailed description of the first modelling approach adopted in this work. Only the main equations are recalled here. A simplified model for wood charring, based on the standard conservation of energy equation, is proposed. The basic differential equation includes a term for each contribution to the internal energy balance.

The energy conservation equation for pyrolysis of the wet wood can be written as following [1,22]:

$$\frac{\partial(\rho C_p T)}{\partial t} = \frac{\partial}{\partial x}\left[\lambda\frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda\frac{\partial T}{\partial y}\right] + Q_r'' \tag{1}$$

where λ is the thermal conductivity; T is the temperature; x and y are the spatial position relative to the surface; t is the time; Q_r'' is the energy source; C_p is the specific heat; ρ is the density of wood.

The boundary conditions of the problem can be of the following types:

$$T = T^* \text{ on } \Sigma_1 \quad (\text{Dirichlettype}) \tag{2}$$

$$\alpha \times q_e'' - q_{loss}'' = \lambda\frac{\partial T}{\partial x} + \lambda\frac{\partial T}{\partial y} \text{ on } \Sigma_2 \quad (\text{Neumanntype}) \tag{3}$$

$$q_{loss}'' = q_{rad}'' + q_{conv}''; \quad q_{rad}'' = \sigma \times \varepsilon \times (T^4 - T_\infty^4); \quad q_{conv}'' = h_{conv} \times (T - T_\infty) \tag{4}$$

where α is the average absorptivity; q_e'' is the external heat flux per area; q_{loss}'' is the heat loss; σ is Stefan–Boltzmann constant; ε is the emissivity; h_{conv} is the convection coefficient and T_∞ is the ambient temperature; T^* is the prescribed temperature defined on a region Ω bounded by a surface $\Sigma = \Sigma_1 + \Sigma_2$. The boundary value problem is a Neumann type if the flux is known on the whole boundary, and the problem is a Dirichlet type if the temperature is known on the whole boundary. Combined boundary conditions are also often encountered: flux is prescribed over some portion of the boundary and temperature is prescribed over the complementary portion of the boundary. Parameters of the model were obtained from the literature using experimental tests.